EFFECT OF BOND ON THE BEHAVIOR OF STEEL FIBRE REINFORCED CONCRETE BEAMS

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ABSTRACT

This paper investigates the effect of concrete-rebar bond and fibre content on the capacity and ductility of steel fibre reinforced concrete beams. In this paper, beams with different proportions of steel fibre and different bar types are tested. Three sets of steel fibre reinforced concrete beams are made with 0%, 1%, and 2% steel fibres by volume. All beams are singly reinforced with three different bar types; deformed bars, plain round bars, and deformed bars unbonded in the central one-third length. All beams are designed for flexure failure, and two equal point loads are applied symmetrically to generate a constant moment region in the central span between the point loads. Test results show that beams containing steel fibres have higher yield load, possess better post-yield load carrying capacity, and are more ductile than the beams made of plain concrete. Although beams with deformed bars possess higher post-yield load carrying capacity and are more ductile than beams with round and unbonded bars, this difference diminishes with the addition of fibres.

KEYWORDS

Steel fibres; SFRC beam; bond; flexure; deformed bars; plain round bars; unbonded bars; ductility

INTRODUCTION

Fine steel fibres mixed in concrete improve the tensile performance of concrete. Fibre reinforced concrete can resist larger tensile stress than normal concrete can. Moreover, fiber reinforced concrete sustains a reasonable proportion of the peak tensile stress (i.e. cracking stress) in the post-cracking phase due mainly to the crack-bridging phenomena [Vandewalle 2000; Mindess et al 2003]. Other advantages of steel fibre reinforced concrete (SFRC) over conventional concrete include increased resistance to cracking, higher energy absorption and higher impact resistance. Nowadays SFRC is used in precast structures, airport runways and taxiway, other industrial slabs, shotcrete and other special structural forms. Even with this wide variety of applications, there are limitations on the use of SFRC in buildings and bridges because of the lack of convincing evidences generated by quality research.

Many experimental and analytical studies can be found on the behaviour of SFRC structures [Hsu et al 1992; Casanova and Rossi 1996; Spadea and Bencardino 1997; Buyle-Bodin and Madhkhan 2002]. These studies were aimed to compare the behaviour of SFRC structures with similar structures made of conventional reinforced concrete (RC) and to investigate if the addition of fibres contributed to significant improvement in the overall structural performance. There are several studies addressing the material behaviour of SFRC [Patton and Whittaker 1983; Horiguchi et al 1988; Haselwander et al 1995], but these studies did not cover a wide range of fibre content and quality, thereby limiting the applicability of the results. Some studies on compression, tension and shear behaviour of SFRC are also available [Lim and Oh 1999; Ding and Kusterle 2000; Vandewalle 2000], but studies addressing the bond behaviour of SFRC are scarce in the authors' knowledge.

Needless to mention, concrete-rebar bond is an important issue in some forms of RC structures. The lack of sufficient bond between concrete and reinforcing bars and the resulting slip may even dictate the failure mode in some cases. To avoid the bond-related deficiencies, concrete design standards require sufficient development length to be provided, or the bar sizes to be limited if the development length is restricted; such as in a beam column joint. It is not yet known if similar measures are needed or if the restrictions can be relaxed when fibre reinforced concrete is used instead of conventional concrete. In this paper, the effect of bond between concrete with different amounts of steel fibres and reinforcing bars of different type is investigated experimentally. The main objectives of the tests are: (i) to investigate the effect of volumetric content of steel fibres on the behaviour of SFRC beams; and (iii) to investigate the effect of different concrete-rebar bond characteristics on the behaviour of SFRC beams.

EXPERIMENT DETAILS

Specimen Details

As the objective of the tests was to investigate the effect of fibre content and concrete-rebar bond on the flexural behaviour of SFRC beams, only the fibre content and the bond conditions were varied in the specimens keeping everything else simple and constant, wherever possible. In total, eighteen reinforced concrete beams were tested. The beams were divided into three sets of six specimens each. The first set consisted of plain RC beams, whereas the second and the third set consisted of SFRC beams with respectively 1% and 2% steel fibres by volume. In each set, two beams were reinforced with round bars, two with deformed bars and the remaining two with deformed bars covered with plastic tube in the central one-third length; referred to as unbonded bars hereafter.

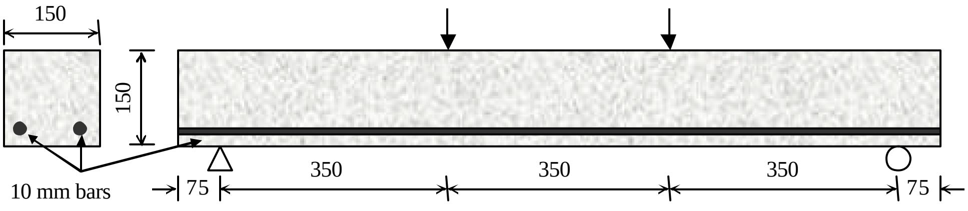

Figure 1 Geometrical and reinforcement details of the specimens (Unit: mm)

The amount and arrangement of reinforcing bars in the three sets were similar. As shown in Fig 1, all beams had 150×150 mm cross-section and were 1200 mm long. Two bars of 10 mm diameter were used as tension reinforcement and a clear cover of 20 mm was provided outside the reinforcing bars. No compression bars and stirrups were used in any of the eighteen beams. The beams were designed to fail in flexure; i.e. shear capacity was designed to be larger than the flexural capacity. As reliable methods to estimate shear capacity of fibre reinforced concrete is not known to the authors, equations meant for calculating shear contribution of normal concrete was used to obtain a conservative estimate of the shear capacity of the tested beams. Calculations using the New Zealand Concrete Standard [NZS3101 1995] showed that the shear capacity of RC beams of similar cross section is 15.5 kN, whereas the shear force induced at yielding of the reinforcing bars when the beam is subjected to two point loads (see Fig 1) is less than 15 kN. Concrete compressive strength of 30 MPa and steel yield strength of 300 MPa are assumed in these calculations.

Fabrication

Figure 2 Formwork and the unbonded bars in the formwork

The formwork was made from a stiffened plywood base with 50 mm thick planks forming six parallel channels to cast the beams in. As shown in Fig 2, these planks were screwed to the base and end plates so that they could be easily taken apart and put together between pours. In the two end plates of the formwork, two holes were made in each channel to insert the two reinforcing bars. Finally the formwork was oiled to make it easier to remove the specimens from the formwork. The unbonded bar was made of standard deformed steel covered by plastic tube as shown in Fig 2. The length of the plastic tube was equal to the length between the two loading points, which was 350 mm. The ends of the tube were sealed using plastic tape, finally resulting in an unbonded zone of approximately 400 mm in the centre of the beam.

There were three batches of concrete in which one was plain concrete and the other two contained 1% and 2% steel fibres by volume. The predetermined amount of steel fibres was added and dispersed throughout the wet concrete by mixing for another 30 to 40 revolutions in the ready-mix truck before pouring on the formwork. Plasticizer was added to enhance the workability of the concrete mix with 2% fibre content. The concrete was vibrated to remove any air entrained in it. In general, concrete with fibres was stiffer and required more vibration. The concrete with 2% fibre content had several clumps of fibre and the workability was significantly low compared with the other two batches. The formwork was stripped one day after casting. The specimens were covered with plastic sheets throughout the curing period to reduce the amount of water evaporation.

Materials

Although ready-mix concrete of 30 MPa compressive strength was ordered, the tested cylinder strengths of various batches varied. The average compressive strength obtained from the standard cylinder (150×300) compression tests was 24.33 MPa for the first batch, 26.8 and 22.25 MPa for the second batch with and without the fibres (1% by volume), and 41.3 and 31.1 MPa for the third batch with and without the fibres (2% by volume).

The steel fibres used in the beams were manufactured by Novocon [www.novocon.com]. These fibres are bright and clean wire of round shape with flattened ends (see Fig 3). They were constructed from cold drawn steel wire of high tensile strength (1150 MPa) and were 30 mm long with 0.7 mm diameter (i.e. aspect ratio of 43).

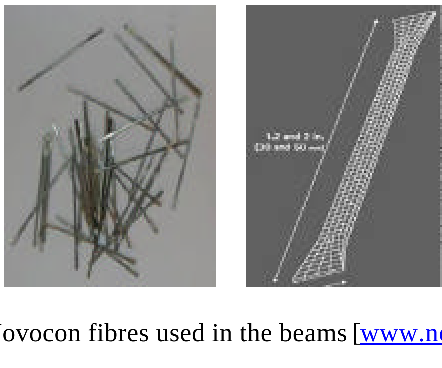

Figure 3 Novocon fibres used in the beams [www.novocon.com]

Plain round bars were used in the first two specimens of each set and deformed bars were used in the rest 4 specimens in each set. For both round and deformed bars used in the beams, the nominal yield strength was 300 MPa. To find the actual yield strength of the bars, tensile tests were conducted on 3 samples for each bar. The average yield strengths of the deformed and round bars were found to be 347.63 and 335.35 MPa, respectively.

Test Set-up and Instrumentation

The 1200 mm long beams were simply-supported between two points located at 75 mm from the two edges; thus making the effective length equal to 1050 mm (see Fig 1). The beams were subjected to two equal point loads applied symmetrically at 175 mm either side from the beam centre. As shown in Fig 4, a 100 kN actuator applied the load and a stiff steel beam was used to divide the load into two halves. The applied load was recorded and the vertical deflection at the mid-span was measured using a potentiometer.

Figure 4 Test setup

RESULTS

Beams without fibre

Fig. 5 shows the load-displacement curves observed from the tests of the beams without any fibre. The result of only one beam with deformed bars is shown because the data from the other test was lost due to technical problems. Before yielding, the deflection of the beams with unbonded bars is slightly higher than the deflection of the other beams under the same load, indicating lower secant stiffness. In fact, there is no smooth load transfer from concrete to rebar after cracking in the central unbonded region. Hence, the beams with unbonded bars release some load after cracking, and this drop of load is reflected throughout the response rendering the load of these unbonded beams smaller than those of beams with deformed and round bars. As expected, the beam with deformed bars had the highest yielding load, followed by the beams with round bars and unbonded bars respectively. This trend was also apparent in the maximum load. One beam containing round bars failed immediately after yielding and the other failed at a deflection slightly less than 20 mm. The failure was indicated by a sudden drop in the load carrying capacity, which is attributed to the loss of bond between the bars and the concrete, thereby reducing the bar stress drastically. The beams with the unbonded bars didn't show any load reduction in the post-yield range until they failed at approximately 20 mm deflection. The beam with deformed bars did not fail in the tested range and exhibited a stable and ductile response.

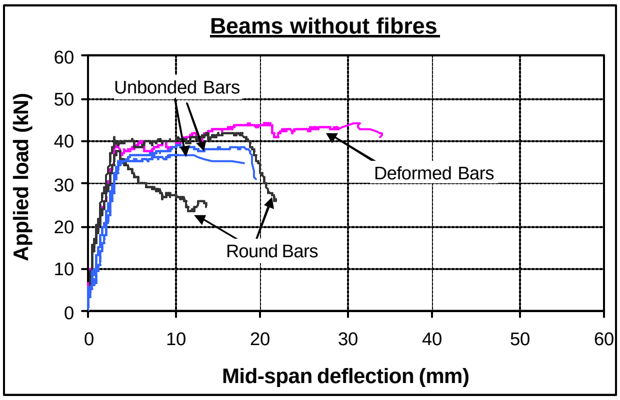

Figure 5 Load-deflection curves for beams without fibre

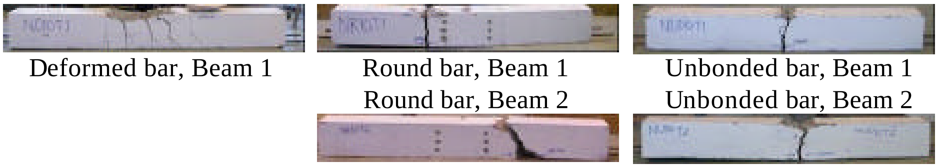

Figure 6 Beams without fibre after the tests

The photographs in Fig. 6 show the physical condition of the beams at the end of the tests. The beam with deformed bars had smaller cracks (approximately 5 mm wide) distributed in the central maximum-moment region, while the other beams had essentially one wide crack (wider than 20 mm). This wide crack was in the central constant-moment region in the two beams with unbonded bars but was outside the central span in the beams with round bars. As the steel stress is constant throughout the central span, the bond demand, which is proportional to the gradient of the rebar stress profile, is likely to be zero. On the other hand, the bond demand is high in the side span due to the linear variation of bending moment and consequently the rebar stress in this region. Hence, it can be argued that the lack of bond in the central span of the unbonded beams does not impair much the performance of the beams. As indicated by the failure plane in the side span, the poor bond between the smooth surface of the round bars and the surrounding concrete could not meet the high bond demand in the side span, and hence these beams experienced bond failure. Although the failure plane in the second beam is slightly inclined, it cannot be shear failure because the inclination is too steep to be a shear crack. The beams with normal and unbonded deformed bars experienced flexural compression failure (see the crushing of concrete at the top of the beams in Fig. 6).

Beams with 1% Fibre

Unlike in the fibreless beams, all six beams with 1% fibre showed ductile behaviour. Nevertheless, performance of the beams with deformed bars was noticeably better than other beams (see Fig. 7). Although the yielding force of beams with round and unbonded bars was slightly higher than that of the beams with deformed bars, the force decreased gradually after yielding. The beams with round bars showed sign of failure after the mid-span deflection exceeded 30 mm. On the other hand, the force sustained by the beams with deformed bars did not decrease after yielding, thereby rendering the force in the post-yielding range larger than that in other beams. Unlike in the previous series, no abrupt release of load was noticed after cracking in the beams with unbonded bars.

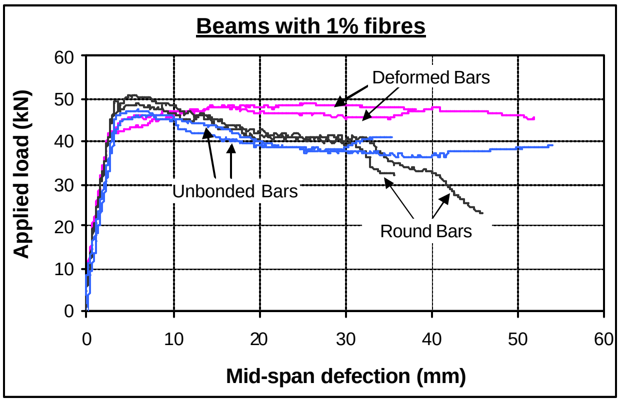

Figure 7 Load-deflection curves for beams with 1% fibre

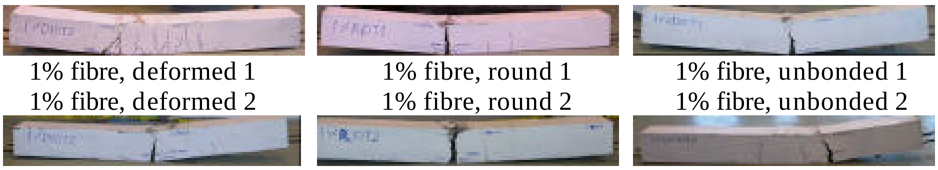

Figure 8 Beams with 1% fibre after the tests

As shown in Fig. 8, the beams with deformed bars had distributed cracks around the centre of the beam. The crack spacing and the crack width were smaller than those obtained in the plain concrete beams. This is in agreement with the findings of Vandewalle [2000], who concluded that the addition of fibres causes a reduction in crack width and spacing. The other beams containing round and deformed bars also started with a few fine cracks but eventually developed only one major crack which led to the failure of the beams. As expected, the major crack leading to the failure of these beams was much wider than the cracks observed in the beams with deformed bars at the end of the tests.

Beams with 2% Fibre

The response of the beams with 2% fibre was similar to those of beams with 1% fibre. As shown in Fig. 9, the beams with round and deformed bars had similar yield capacities. The beams with deformed bars sustained the yield load after yielding whereas the load of the beams with round and unbonded bars decreased in the post-yielding range. The ductility of the beams with unbonded bars was less than that of the beams with deformed bars but greater than that of the beams with round bars.

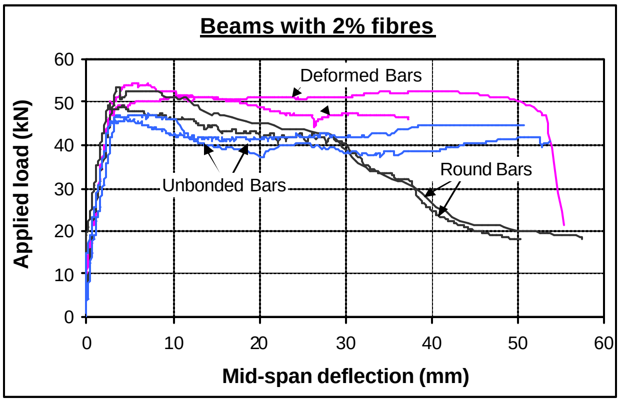

Figure 9 Load-deflection curves for beams with 2% fibre

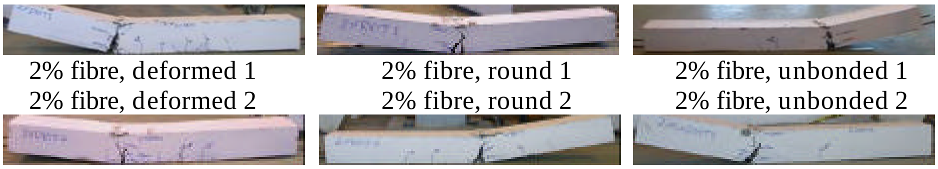

Figure 10 Beams with 2% fibre after the tests

In all beams, multiple distributed cracks were observed in the early stage. As can be seen in Fig 10, more cracks emerged on the beam with deformed bars than in other beams. Nevertheless, only one of these cracks widened and governed the behaviour of the beams in the later stage leading to failure. The major crack was under one of the loading points in all beams except those with round bars, in which it was in the central span. As in the previous series, the width of the crack was small in the beam with deformed bars when compared to the crack width in the other beams at the same loading stage.

DISCUSSIONS

Although the difference between the calculated shear and flexural capacities was small, no shear cracks were observed and all beams failed in flexure. All beams exceeded their calculated capacity of approximately 15 kN which corresponds to a total applied load of 30 kN. Flexural cracks initiated in the maximum moment region when the displacement reached about 1 mm. In beams with deformed bars, several cracks gradually appeared in the central maximum-moment region whereas in other beams with round and unbonded bars, one major and wide crack led to the ultimate failure.

As can be seen in Figures 5, 7 and 9, increasing the fibre content from 0% to 1%, and from 1% to 2%, the yield strengths of the beams increased, irrespective of the bar type. This is due to the higher tensile and compressive stresses carried by fiber reinforced concrete compared to plain concrete [Ding and Kusterle 2000; Lim and Oh 1999]. With addition of steel fibres, changes are also observed in the post-yield load capacity. The beams containing fibre had higher load than the plain concrete beams had at the same deflection. This trend was apparent for all types of bars. It indicates that the use of fibre has a significant effect in improving the post-yield behaviour; mainly ductility. The reason for this behaviour is because compared to plain concrete SFRC can sustain larger compressive strain with less reduction of compressive stress [Ding and Kusterle 2000]. Another reason can be that unlike plain concrete which can not carry any tensile stress after cracking the fibres can still effectively transfer some tensile load across the cracks through bridging action [Vandewalle 2000; Mindess et al 2003].

On the other hand, type of reinforcing bars does not have a pronounced effect on the yield load and corresponding displacement, but appears to have more distinct effect on the post-yield load carrying capacity and ductility. All beams with deformed bars had relatively stable post-yield load carrying capacity. As the plain concrete beam with deformed bars maintained the yielding load in the tested range, the effect of fibre content on ductility was not clear although it apparently had a pronounced effect on the capacity. The plain concrete beams with round bars were found to have a lower yielding load, and they also failed soon after yielding showing brittle bond failure. Despite the poor bond of the smooth surface of round bars, the SFRC beams sustained more than 80% of the yield load in the post-yield range until the deflection exceeded 30 mm. The difference between the responses of the beams with deformed and round bars was far less in SFRC beams than in the plain concrete beams. This indicated that the concrete-rebar bond has less influence on the behaviour of SFRC beams. This argument is also supported by the improved post-yield response of the beams with unbonded bars when fibres were added.

The beams with unbonded bars had higher post-yield load capacity and ductility compared to the beams with round bar. A possible reason for this is that these beams had deformed bars wrapped in a tube throughout the constant-moment zone, and these deformed bars were exposed in the side spans where they had better bond than the round bars did. As the bond demand is zero in the central span and high in the side span, the unbonded beams might have had better performance than the round bar beams.

CONCLUSIONS

Reinforced concrete beams without fibres and with 1% and 2% steel fibres and reinforced with three different types of bars (deformed bars, round bars and deformed bars wrapped in a plastic tube in the central one-third span) were tested. Although the shear and flexural capacities calculated by neglecting the fibre contribution were close, diagonal shear cracks did not emerge and the beams failed by either flexure or bond. The behaviour of the beams with round and unbonded deformed bars was mainly dictated by one major crack, although more than one cracks initially emerged in these beams when steel fibres were added. In the beams with deformed bars, multiple flexural cracks were observed regardless of the fibre content.

The beams with deformed bars showed ductile behaviour and did not fail in the tested range. The beams with unbonded deformed bars failed in flexure in all three series, but the ductility increased with the addition of fibres. Similarly, addition of fibres also tremendously enhanced the post-yield performance of the beams with round bars. The beams with round bars and without fibres experienced bond failure in a brittle manner, whereas the SFRC beams failed in flexure after undergoing significant post-yield deformation. As expected, the addition of fibres increased the yielding capacity and the peak capacity. More importantly, the SFRC beams showed ductile behaviour regardless of the bar type. The effect of concrete-rebar bond was less influential in SFRC beams.

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